NuFact 2013

IHEP, Beijing, August 21st 2013

Charged Lepton Flavor Violation
Brief Theory Overview

Lorenzo Calibbi

ULB

Why going beyond the Standard Model?

- Hierachy Problem (?)
- Dark Matter/Dark Energy
- Inflation
- Neutrino masses
- Baryon asymmetry
- Origin of flavor hierarchies

...

Why going beyond the Standard Model?

- Hierachy Problem (?) → TeV-scale New Physics?
- Dark Matter/Dark Energy
- Inflation
- Neutrino masses → See-saw?
- Baryon asymmetry → Leptogenesis?
- Origin of flavor hierarchies → Symmetries of flavor?

...

Testable through Lepton Flavor Violation?

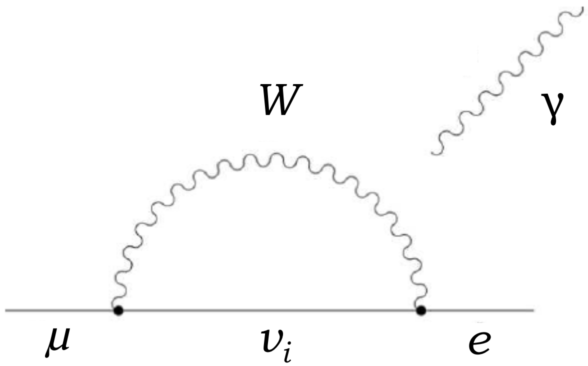
Introduction: why LFV?

- Neutrinos oscillate → Lepton family numbers are not conserved!

- Can we observe LFV in charged leptons decays?

- In the SM + massive neutrinos:

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{\rm em}}{32\pi}\left|\sum_i U_{\mu i} U_{ei} \frac{m_{\nu_i}^2}{M_W^2}\right|^2$$



⇨ $\mathrm{BR}(\mu \to e\gamma) \lesssim \mathcal{O}(10^{-50})$

Suppression due to small neutrino masses

Cheng Li ’77, ’80; Petcov ‘77

⇨ In presence of NP at the TeV we can expect large effects!

Introduction: why LFV?

- Unambigous signal of New Physics
- Stringent test of NP models
- It probes scales far beyond the LHC reach:

$\mathrm{BR}(\mu \to e\gamma) < 5 \times 10^{-14}$

Process	Relevant operators	Present Bound on Λ (TeV)		Future Bound on Λ (TeV)	
		$C = 1/16\pi^2$	$C = 1$	$C = 1/16\pi^2$	$C = 1$
$\mu \to e\gamma$	$\frac{C}{\Lambda^2}\frac{m_\mu}{16\pi^2}\overline{\mu}_L\sigma^{\mu\nu}e_R F_{\mu\nu}$	50	—	90	—
$\mu \to eee$	$\frac{C}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{e}_L\gamma^\mu e_L)$	17	210	170	2100
	$\frac{C}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{e}_R e_L)$	10	120	100	1200
$\mu \to e$ in Ti	$\frac{C}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{d}_L\gamma^\mu d_L)$	30	420	580	7300
	$\frac{C}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{d}_R d_L)$	60	750	1000	13000

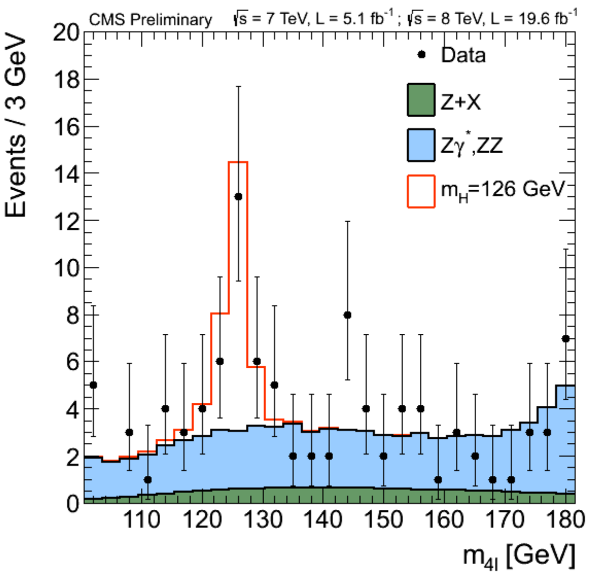
$\mathrm{BR}(\mu \to eee) < 10^{-16}$

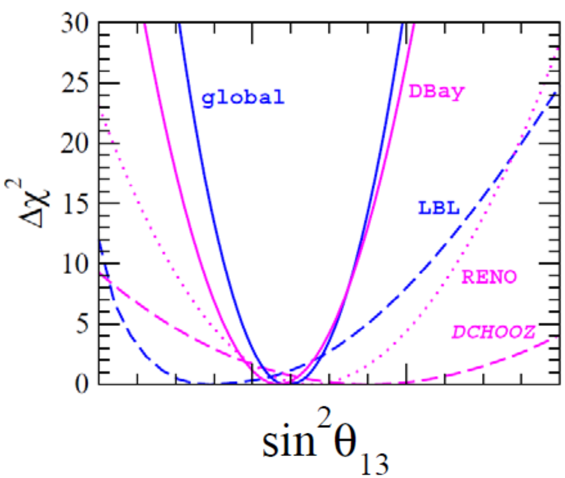
$\mathrm{CR}(\mu \to e \text{ in Ti}) < 5 \times 10^{-17}$

updated from LC Lalak Pokorski Ziegler '12

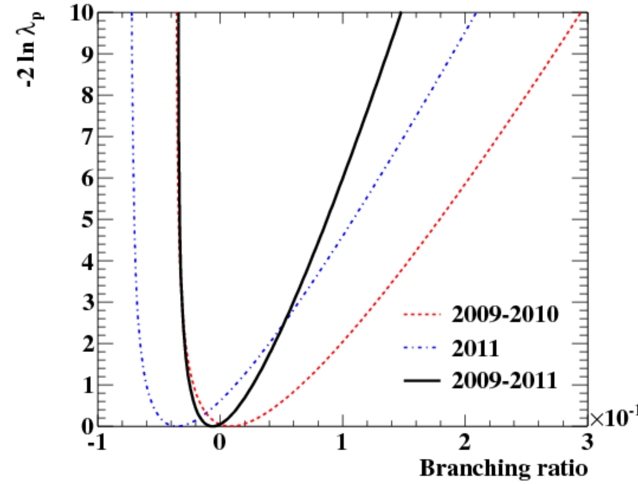
Experimental News

SM-like Higgs!	PMNS reactor angle:	MEG limit:
$m_h \approx 126\,\mathrm{GeV}$	$\theta_{13} \approx 9^{\mathrm{o}}$	$\mathrm{BR}(\mu^+ \to e^+\gamma) < 5.7 \times 10^{-13}$



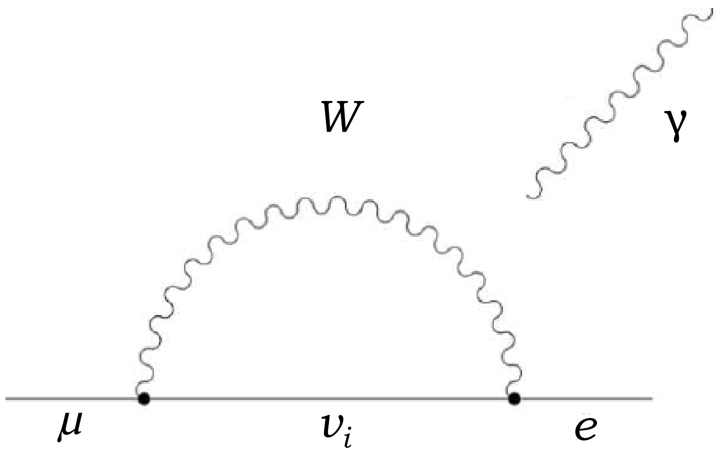


Forero et al. ‘12



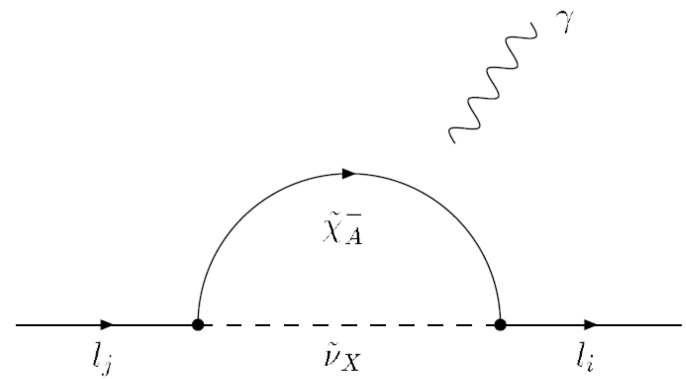
MEG ‘13

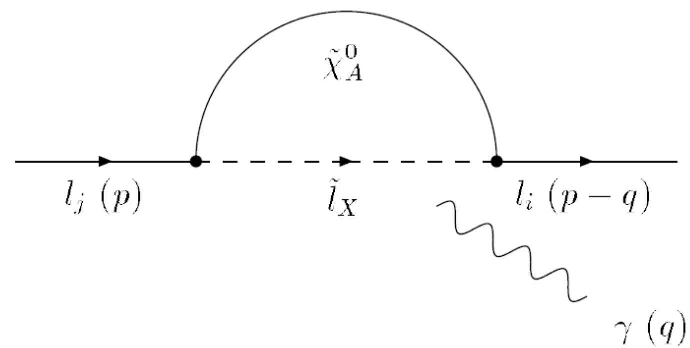
CLFV in SUSY models



$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{\rm em}}{32\pi}\left|\sum_i U_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W}\right|^2$$

SUSY $\Rightarrow$



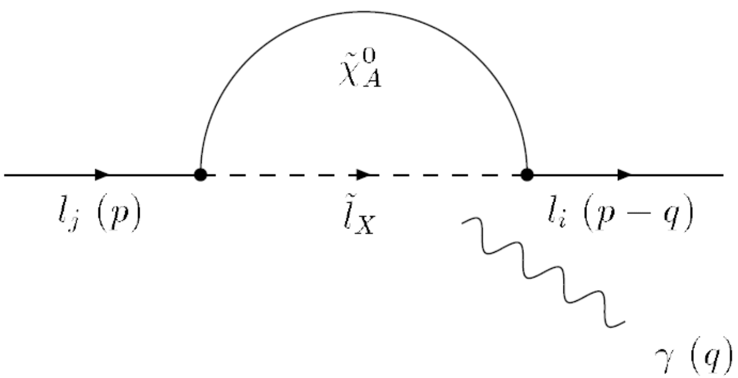


Borzumati Masiero '86;
Hisano et al. '95

$\boxed{\text{Flavour violation induced by misalignment between leptons and sleptons}}$

Slepton mass matrix:

$$m^2_{\tilde{\ell}} = \begin{pmatrix} (\tilde{m}^2_L)_{ij} + (m^2_\ell)_{ij} - m^2_Z(\frac{1}{2} - \sin^2\theta_W)\delta_{ij} & A^{\ell\,*}_{ji} v_d - (m_\ell)_{ji}\mu\tan\beta \\ A^\ell_{ij} v_d - (m_\ell)_{ij}\mu^*\tan\beta & (\tilde{m}^2_E)_{ij} + (m^2_\ell)_{ij} - m^2_Z \sin^2\theta_W \delta_{ij} \end{pmatrix}$$



$\Rightarrow$ $$BR(\ell_i \to \ell_j\gamma) = \frac{48\pi^3\alpha_{\rm em}}{G_F^2}\left(|C_L^{ij}|^2 + |C_R^{ij}|^2\right) BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)$$

Hisano et al. '95

$$\boxed{C_L^{ij} \sim \frac{g^2}{16\pi^2}\frac{(\tilde{m}^2_L)_{ij}}{\tilde{m}^4}\tan\beta}$$

Two ingredients:
flavor structure of soft terms & the SUSY mass-scale

The flavor structure of slepton mass matrices might be:

• anarchical (MEG constraints slepton masses to be > O(50) TeV !)

• controlled by the same dynamics that gives riase to Yukawas (e.g. a flavor symmetry: $SU(3)_F$, $U(2)_F$, A_4 ...)

• trivial (no flavor mixing): yet slepton masses are sensitive to very high-energy physics → radiative corrections can induce large LFV

Overall suppression given by slepton and neutralino/chargino masses:

• EW-interacting states, relatively weakly constraned by LHC experiments (e.g. slepton masses > 200÷300 GeV)

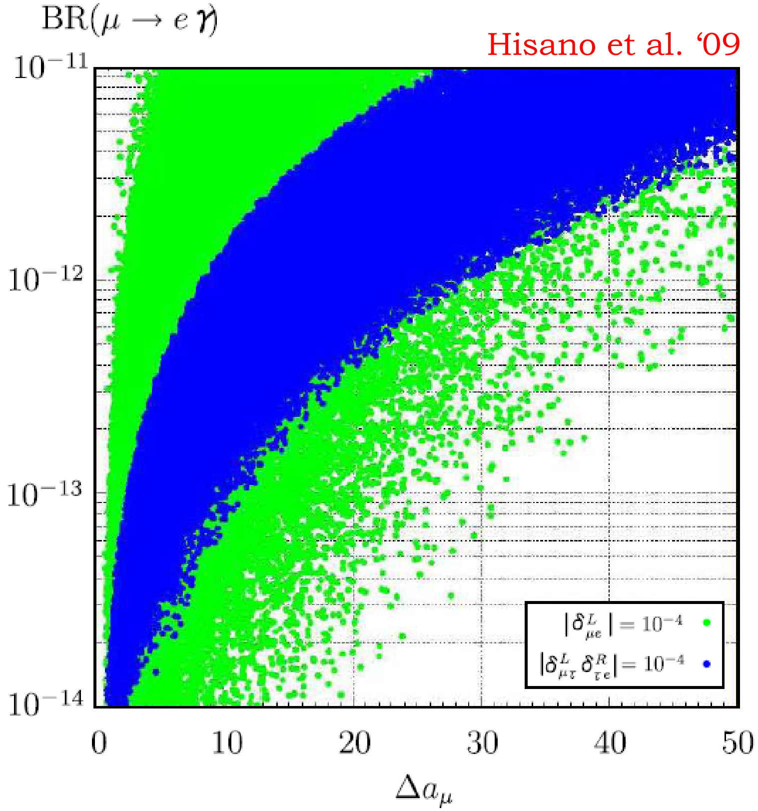
• SUSY solution of $(g\text{-}2)_\mu$ requires sleptons etc. below 1 TeV

Same dipole operator: correlation with $(g\text{-}2)_\mu$!

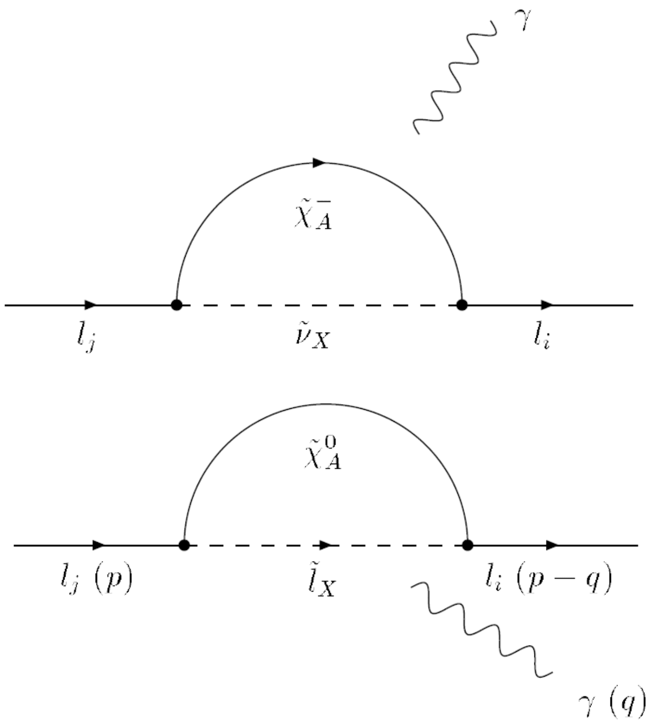
$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = 2.90(90)\times 10^{-9}\,, \qquad \textbf{3.5}\sigma\ \textbf{discrepancy}$$

$$\mathrm{BR}(\mu\to e\gamma) \;\approx\; 2\times 10^{-12}\left[\frac{\Delta a_\mu^{\rm SUSY}}{3\times 10^{-9}}\right]^2 \left|\frac{\delta^L_{\mu e}}{10^{-4}}\right|^2$$

Hisano et al. '09

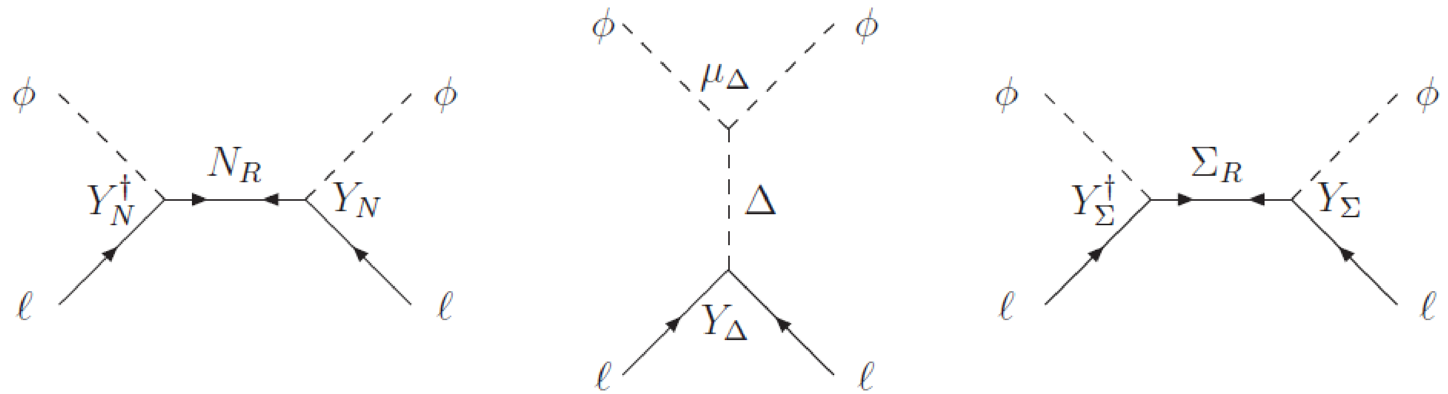


Hisano Nagai Paradisi Shimizu '09



(SUSY) Seesaw Mechanism

Tree level generation of the neutrino mass operator $\boxed{\frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{\ell^c_{L\alpha}}\,\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\, \ell_{L\beta}\right)}$:



Type I
Heavy fermionic singlets (RH neutrinos)

Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic, ...

Type II
Heavy scalar triplet

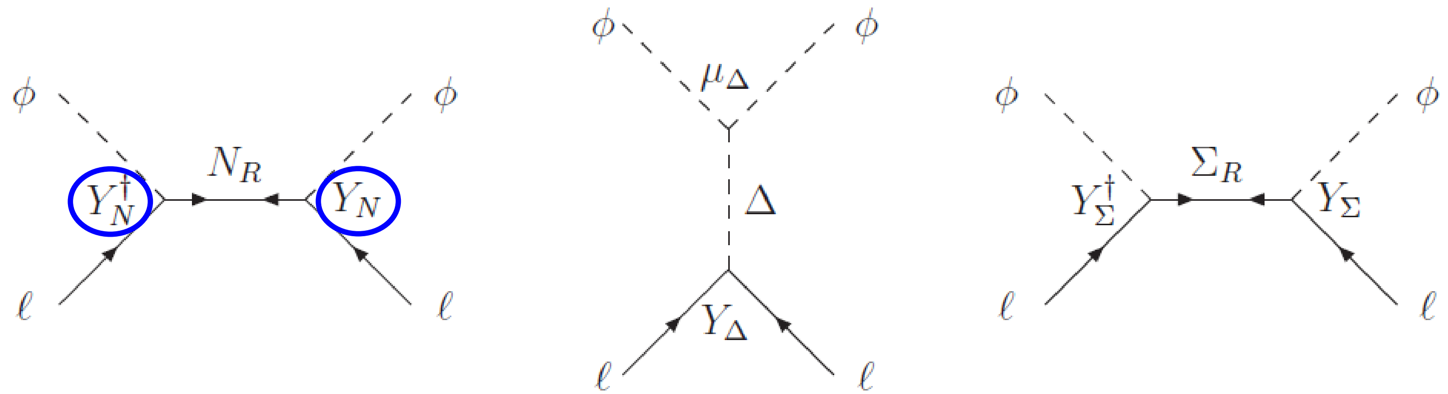
Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle, ...

Type III
Heavy fermionic triplets

Foot, Lew, He, Joshi, Ma, Roy, Hambye et al., Bajc et al., Dorsner, Fileviez-Perez, ...

→ B. Gavela, F. Joaquim talks

Tree level generation of the neutrino mass operator $\boxed{\frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{\ell^c_{L\alpha}}\,\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\, \ell_{L\beta}\right)}$:



Type I
Heavy fermionic singlets (RH neutrinos)

Type II
Heavy scalar triplet

Type III
Heavy fermionic triplets

Type I (SUSY):

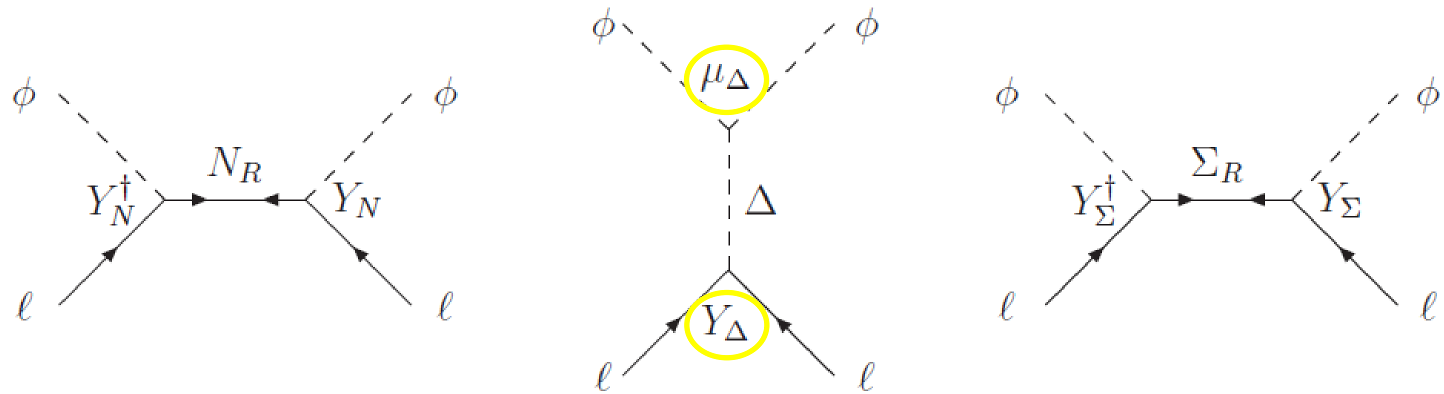
$$W_{\rm I} = W_{\rm MSSM} + (\mathbf{Y}_N)_{ij}\, N_i L_j H_u - \frac{1}{2}(\mathbf{M}_R)_{kk}\, N_k N_k$$

$$\Rightarrow \quad \mathbf{m}_\nu = \mathbf{Y}_N{}^T \mathbf{M}_R{}^{-1} \mathbf{Y}_N v_u^2 \qquad \boxed{\mathbf{Y}_N = \frac{1}{v_u}\sqrt{\mathbf{M}_R}\,\mathbf{R}\,\sqrt{\hat{\mathbf{m}}_\nu}\, U^\dagger_{\rm PMNS}}$$

Mismatch between low and high-energy params. Casas Ibarra '01

(SUSY) Seesaw Mechanism

Tree level generation of the neutrino mass operator $\boxed{\frac{1}{2}\, c^{d=5}_{\alpha\beta}\, \left(\overline{\ell^c_{L\alpha}}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\,\ell_{L\beta}\right)}$:



Type I	Type II	Type III
Heavy fermionic singlets (RH neutrinos)	Heavy scalar triplet	Heavy fermionic triplets

Type II (SUSY): $$W_{\rm II} = W_{\rm MSSM} + \frac{1}{\sqrt{2}}(\mathbf{Y}_\Delta)_{ij}\, L_i \Delta L_j + \frac{1}{\sqrt{2}}\lambda\, H_u \Delta H_u + M_\Delta\, \Delta\Delta$$

$$\Rightarrow \quad \mu_\Delta = \lambda \frac{M_\Delta}{\sqrt{2}} \qquad \boxed{(\mathbf{m}_\nu)_{ij} = \frac{\lambda v_u^2}{M_\Delta}\,(\mathbf{Y}_\Delta)_{ij}}$$

Direct link to the light neutrino mass matrix! In principle all parameters known

LFV in SUSY seesaw

In SUSY, new fields interacting with the MSSM fields enter the radiative corrections of the sfermion masses

Hall Kostelecky Raby '86

⇨ This applies to the new seesaw interactions: generically induce LFV in the slepton mass matrix!

Borzumati Masiero '86

Type I

$$(\tilde{m}^2_L)_{ij} \propto m_0^2 \sum_k (\mathbf{Y}_N^*)_{ki} (\mathbf{Y}_N)_{kj} \ln\left(\frac{M_X}{M_{R_K}}\right)$$

Borzumati Masiero '86

Type II

$$(\tilde{m}^2_L)_{ij} \propto m_0^2 (\mathbf{Y}_\Delta{}^\dagger \mathbf{Y}_\Delta)_{ij} \ln\left(\frac{M_X}{M_\Delta}\right) \propto m_0^2 (\mathbf{m}_\nu{}^\dagger \mathbf{m}_\nu)_{ij} \ln\left(\frac{M_X}{M_\Delta}\right)$$

A. Rossi '02; Rossi Joaquim '06

Type III

Similar to type I

Biggio LC '10; Esteves et al. '10

→ F. Joaquim talk

Type II: consequences of a large θ_{13}

Type II : direct connection between seesaw couplings and the PMNS.

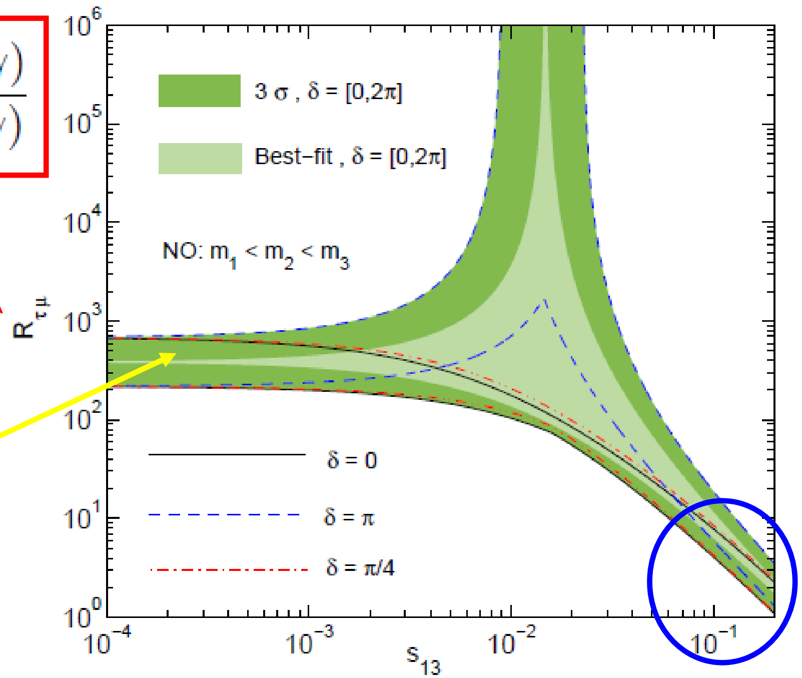
Hierarchical neutrinos normal ordering (IO similar):

$$\mathrm{BR}(\mu \to e\gamma) \propto \left|\Delta m^2_{31}\, s_{\theta_{13}} c_{\theta_{13}} s_{\theta_{23}} + \Delta m^2_{21}\, s_{\theta_{12}} c_{\theta_{13}} (c_{\theta_{12}} c_{\theta_{23}} - s_{\theta_{12}} s_{\theta_{13}} s_{\theta_{23}})\right|^2$$

$$\mathrm{BR}(\tau \to \mu\gamma) \propto \left|\Delta m^2_{31}\, c^2_{\theta_{13}} c_{\theta_{23}} s_{\theta_{23}} + \mathcal{O}(\Delta m^2_{12})\right|^2$$

$$R_{\tau\mu} \equiv \frac{\mathrm{BR}(\tau \to \mu\gamma)}{\mathrm{BR}(\mu \to e\gamma)}$$

$$\left(\frac{\Delta m^2_{31}}{\Delta m^2_{21}}\right)^2$$



Joaquim '09

Taking the 2σ ranges of Forero Tortola Valle '12 we get:

$$R_{\tau\mu} \lesssim 6$$

MEG '13 limit implies:

$$\mathrm{BR}(\tau \to \mu\gamma) < 10^{-11}$$

beyond the reach of foreseeable experiments!

Type I: θ_{13} dependence

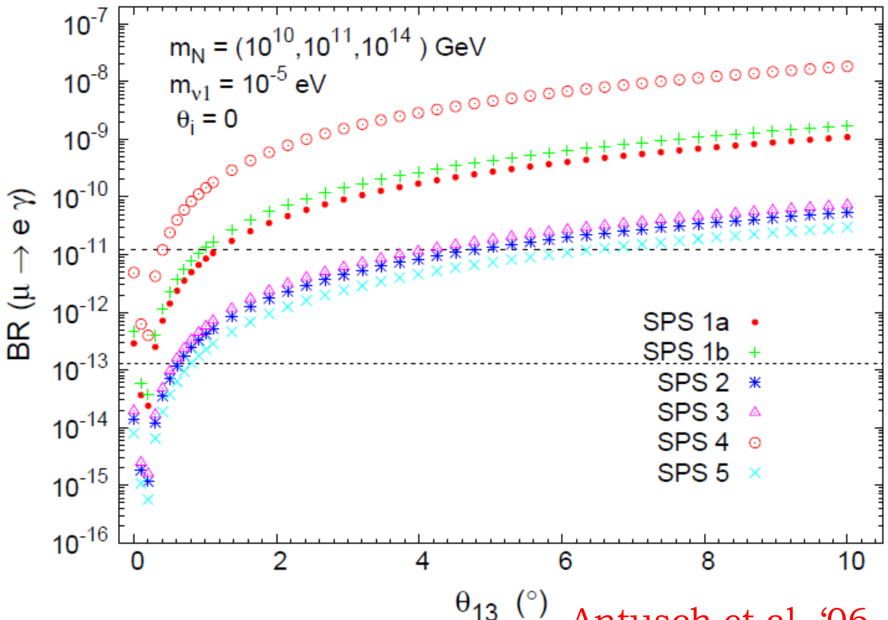
$\boxed{\text{Type I}}$: in general the connection between seesaw couplings and the PMNS is 'washed out' by the matrix R Casas et al '10

However, theoretically motivated examples where the correlation is there:

- Trivial mixing from RHν (i.e. R~**1**) :

$$\Rightarrow \quad \mathrm{BR}(\mu \to e\gamma) \propto \left|(y_k^N)^2 \, U_{\mu k} U_{ek}^*\right|^2$$

(hierarchical RHν → k=3)



Antusch et al. '06

Type I: θ_{13} dependence

Type I : in general the connection between seesaw couplings and the PMNS is 'washed out' by the matrix R Casas et al '10

However, theoretically motivated examples where the correlation is there:

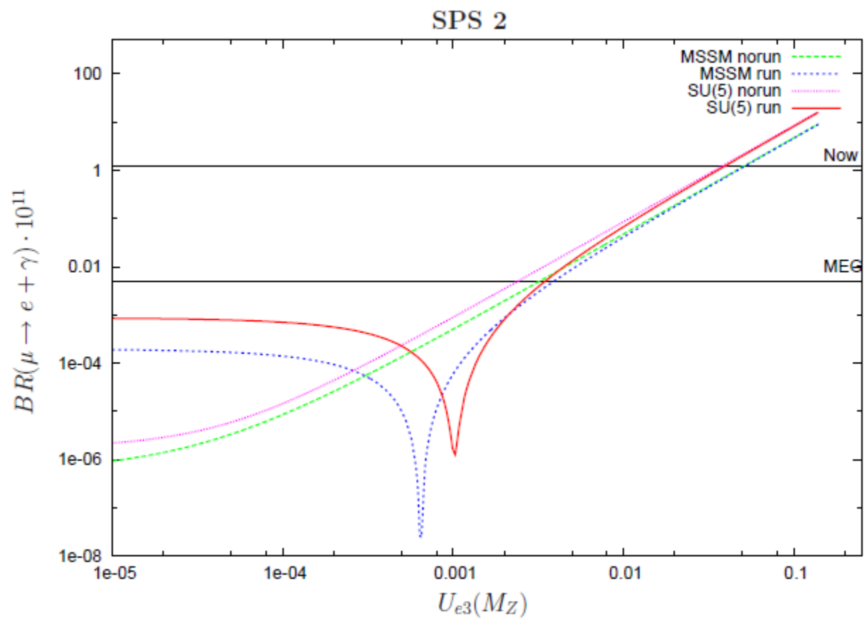
- SO(10) GUT ('PMNS mixing' case): Chang Masiero Murayama '02; Masiero Vives Vempati '02

$$W = \frac{1}{2}(Y_u)_{ij}16_i 16_j 10_u + \frac{1}{2}(Y_d)_{ij}16_i 16_j \frac{\langle 45 \rangle}{M_{Pl}} 10_d$$

$$\Downarrow$$

$$\boxed{\mathbf{Y}_N = U_{\text{PMNS}}\,\mathbf{Y}_u^{\text{diag}}}$$

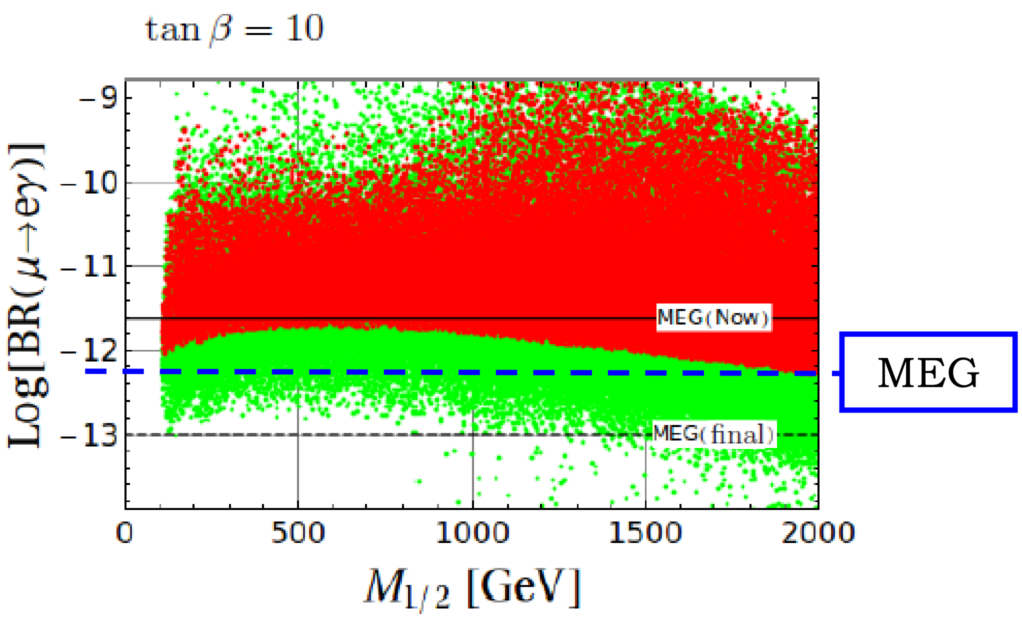
$$\text{BR}(\mu \to e\gamma) \propto \left| y_t^2 U_{\mu 3} U_{e3}^* \right|^2$$



LC Faccia Masiero Vempati '06

MEG vs. LHC bounds

- SO(10) GUT ('PMNS mixing' case): $\mathrm{BR}(\mu \to e\gamma) \propto \left| y_t^2\, U_{\mu 3} U_{e3}^* \right|^2$



LC Chowdhury Masiero Patel Vempati '12

$$m_0 \in [0,\ 5]\ \mathrm{TeV}$$

$$\Delta m_H \in \begin{cases} 0 & \text{for mSUGRA} \\ [0,\ 5] & \text{for NUHM1} \end{cases}$$

$$m_{1/2} \in [0.1,\ 2]\ \mathrm{TeV}$$

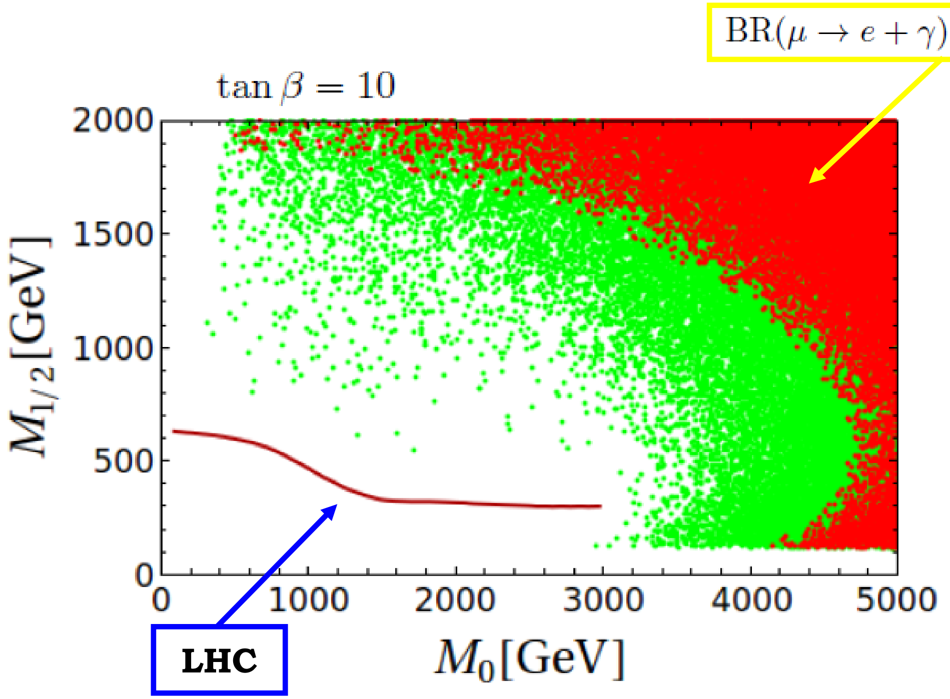
$$A_0 \in [-3m_0,\ +3m_0]$$

$$\mathrm{sgn}(\mu) \in \{-,+\}$$

$$\boxed{|U_{e3}| = 0.11}$$

$$\boxed{124.5\ \mathrm{GeV} \lesssim m_h \lesssim 126.5\ \mathrm{GeV}}$$

- SO(10) GUT ('PMNS mixing' case): $\mathrm{BR}(\mu \to e\gamma) \propto \left| y_t^2 \, U_{\mu 3} U_{e3}^* \right|^2$



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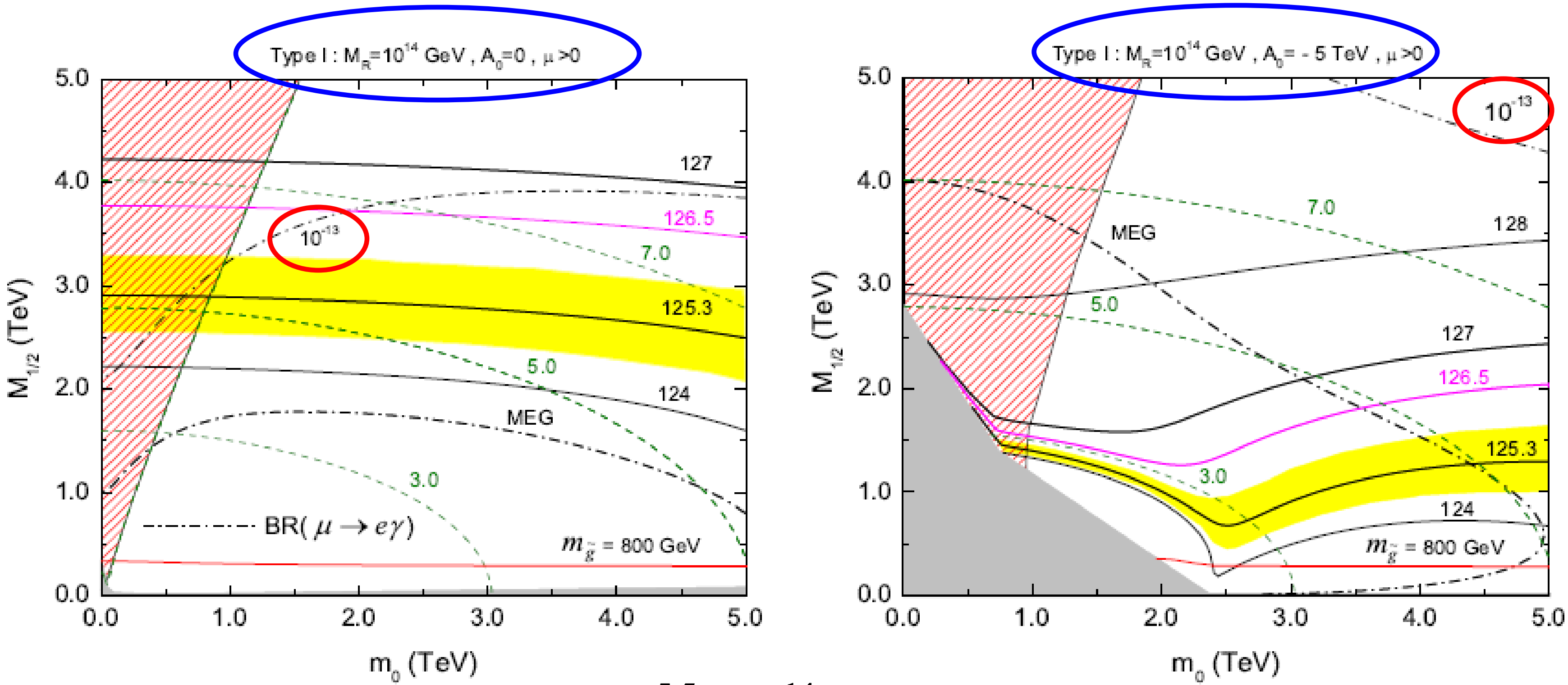
$$|U_{e3}| = 0.11$$

$$124.5\ \mathrm{GeV} \lesssim m_h \lesssim 126.5\ \mathrm{GeV}$$

- Trivial mixing from RHν (R=**1**):



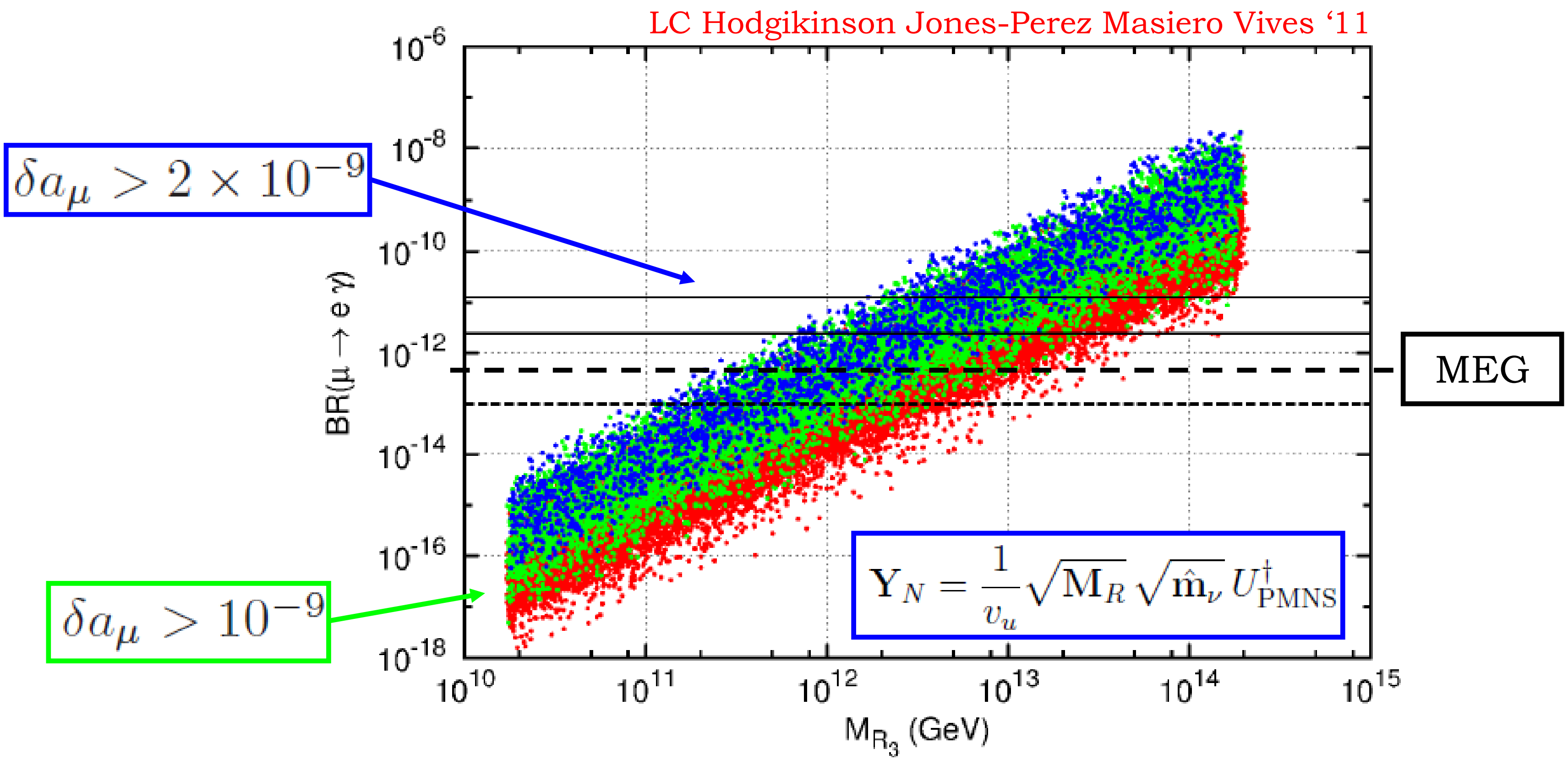
Hirsch Joaquim Vicente '12

M_R=10^{14} GeV

→ F. Joaquim talk

MEG vs. g-2

- Trivial mixing from RHν (*R*=**1**), with light sleptons:



SUSY g-2 compatible with MEG only if $\mu \to e\gamma$ suppressed:

$M_R < 10^{12 \div 13}$ GeV

- **NP effects are encoded in the effective Lagrangian**

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R\sigma_{\mu\nu}A_{\ell\ell'}\ell'_L + \bar{\ell}'_L\sigma_{\mu\nu}A^\star_{\ell\ell'}\ell_R\right)F^{\mu\nu} \qquad \ell,\ell' = e,\mu,\tau\,,$$

$$A_{\ell\ell'} = \frac{1}{(4\pi\,\Lambda_{\rm NP})^2}\left[\left(g^L_{\ell k}\,g^{L*}_{\ell' k} + g^R_{\ell k}\,g^{R*}_{\ell' k}\right)f_1(x_k) + \frac{v}{m_\ell}\left(g^L_{\ell k}\,g^{R*}_{\ell' k}\right)f_2(x_k)\right]\,,$$

  - **Δa_ℓ and leptonic EDMs are given by**

$$\Delta a_\ell = 2m_\ell^2\,\mathrm{Re}(A_{\ell\ell}), \qquad \frac{d_\ell}{e} = m_\ell\,\mathrm{Im}(A_{\ell\ell})\,.$$

  - **The branching ratios of $\ell \to \ell'\gamma$ are given by**

$$\frac{\mathrm{BR}(\ell\to\ell'\gamma)}{\mathrm{BR}(\ell\to\ell'\nu_\ell\bar{\nu}_{\ell'})} = \frac{48\pi^3\alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right)\,.$$

- **"Naive scaling":** Giudice Passera Paradisi '12

$$\Delta a_{\ell_i}/\Delta a_{\ell_j} = m^2_{\ell_i}/m^2_{\ell_j}, \qquad d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}\,.$$

- $(g-2)_\ell$ **assuming "Naive scaling"** $\Delta a_{\ell_i}/\Delta a_{\ell_j} = m^2_{\ell_i}/m^2_{\ell_j}$

$$\Delta a_e = \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)0.7\times 10^{-13}, \qquad \boxed{\Delta a_e = a_e^{\rm EXP} - a_e^{\rm SM} = -10.6\,(8.1)\times 10^{-13}}$$

from P. Paradisi's talk at the 1st Conference on CLFV, Lecce 2013

- **Challenge**: Large effects for $g-2$ keeping under control $\mu \to e\gamma$ and d_e
- **"Disoriented A-terms"** [Giudice, Isidori & P.P., '12]:

$$(\delta^{ij}_{LR})_f \sim \frac{A_f \theta^f_{ij} m_{f_j}}{m_{\tilde{f}}} \qquad f = u, d, \ell \; ,$$

  - Flavor and CP violation is restricted to the trilinear scalar terms.
  - Flavor bounds of the down-sector are naturally satisfied thanks to the smallness of down-type quark/lepton masses.
  - This ansatz arises in scenarios with partial compositeness where we a natural prediction is $\theta^{\ell}_{ij} \sim \sqrt{m_i/m_j}$ [Rattazzi et al.,'12].

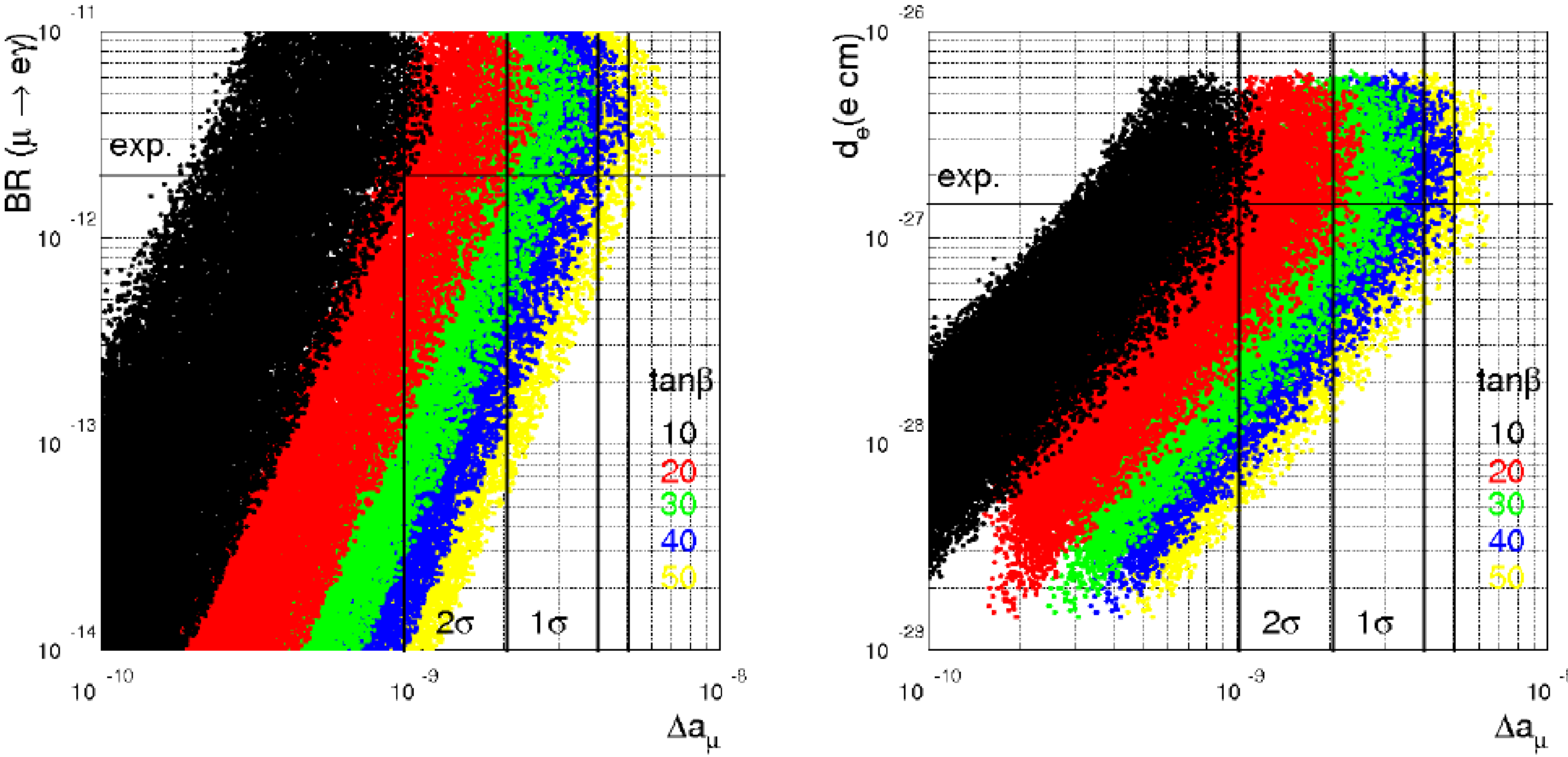
- $\mu \to e\gamma$ and d_e are generated only by $U(1)$ interactions

$$A_L^{\mu e} \sim \frac{\alpha}{\cos^2\theta_W}\,\delta^{\mu e}_{LR}\,, \qquad \frac{d_e}{e} \sim \frac{\alpha}{\cos^2\theta_W}\,\mathrm{Im}\delta^{ee}_{LR}\,.$$

- $(g-2)_\mu$ is generated by $SU(2)$ interactions and is $\tan\beta$ enhanced therefore the relative enhancement w.r.t. $\mu \to e\gamma$ and d_e is $\tan\beta/\tan^2\theta_W \approx 100 \times (\tan\beta/30)$

$$\Delta a_\ell \sim \frac{\alpha}{\sin^2\theta_W}\,\tan\beta$$

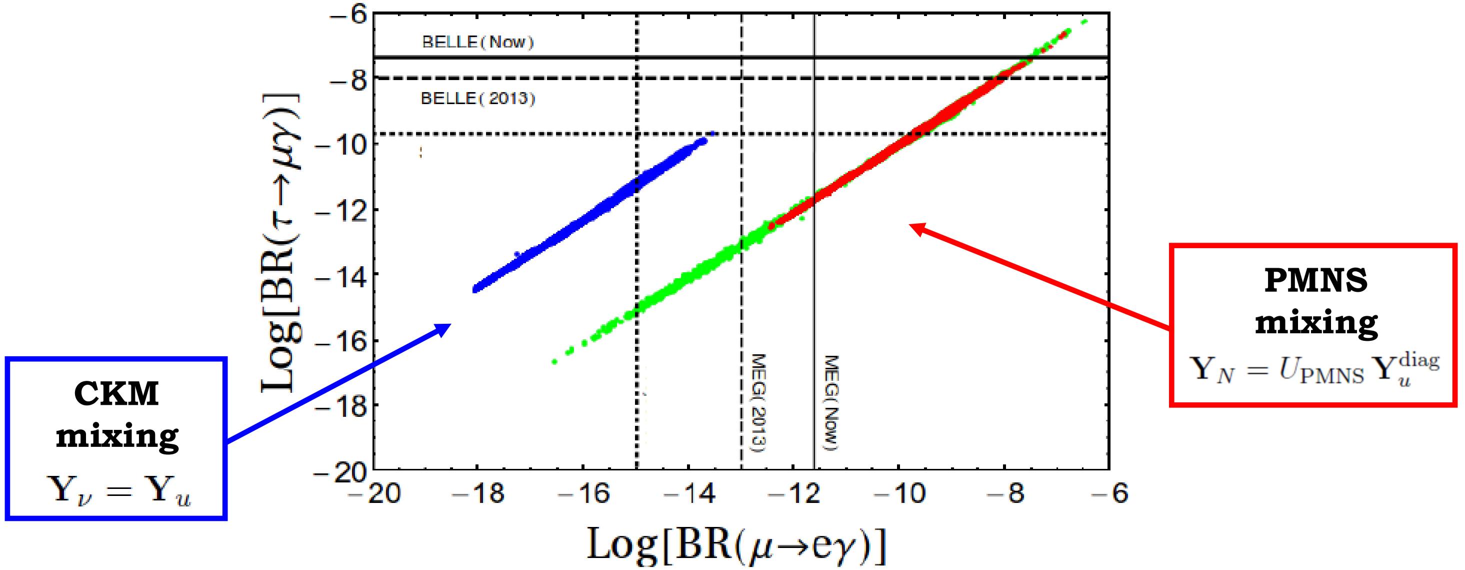
from P. Paradisi's talk at the 1st Conference on CLFV, Lecce 2013



Predictions for $\mu \to e\gamma$, Δa_μ and d_e in the disoriented A-term scenario with $\theta^\ell_{ij} = \sqrt{m_i/m_j}$. Left: $\mu \to e\gamma$ vs. Δa_μ. Right: d_e vs. Δa_μ

Giudice Passera Paradisi '12

τ-μ vs. μ-e transitions



Scenarios that could 'naturally' suppress $\mu \to e$ transitions relative to $\tau \to \mu$ cannot be realized with $\theta_{13} \sim O(0.1)$

Random variation of matrix R and neutrino parameters:

$$\frac{\mathrm{BR}(\tau \to \mu\gamma)}{\mathrm{BR}(\mu \to e\gamma)} \lesssim \mathcal{O}(1000) \Longrightarrow \mathrm{BR}(\tau \to \mu\gamma) \lesssim \mathcal{O}(10^{-9})$$

DayaBay/Reno measurements imply that SUSY seesaw(s) can be preferably tested through $\mu \to e$ transitions

Correlations in the μ-e sector

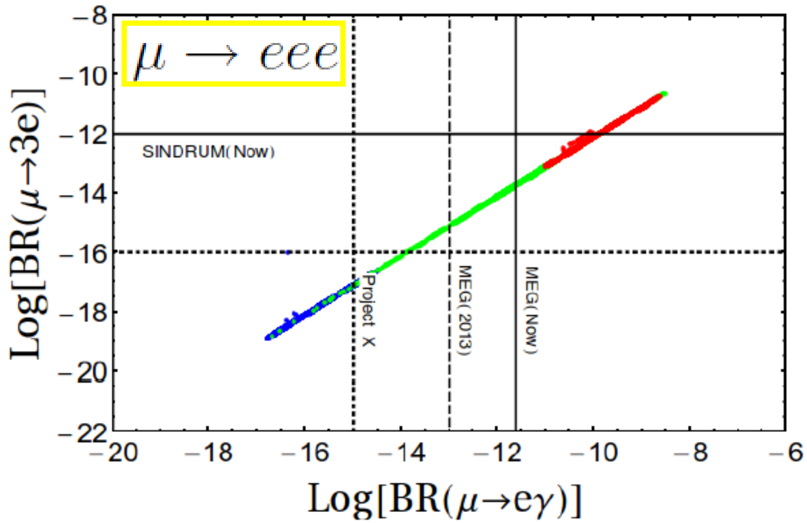
In SUSY (with R_P) $\mu\to eee$ and $\mu\to e$ conversion dominated by the dipole $\mu\to e\gamma$*

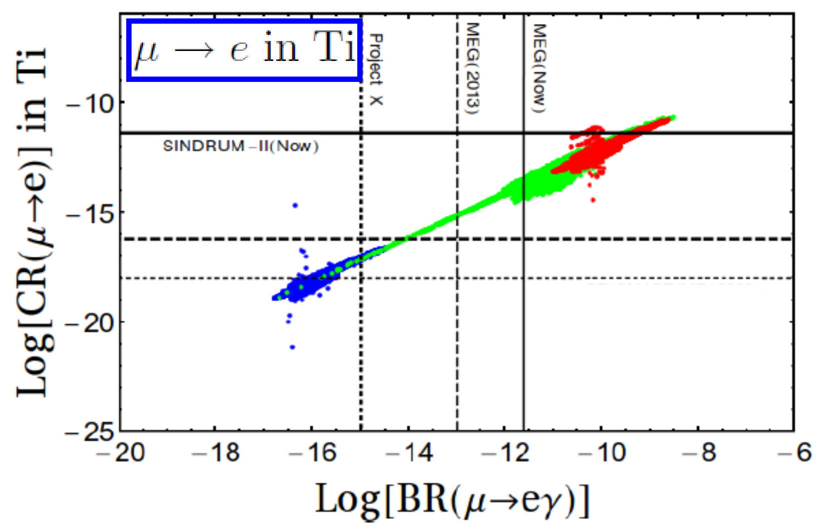
Strong correlations:

not only seesaw models!

$$\boxed{\begin{aligned} \mathrm{BR}(\mu\to eee) &\sim \alpha_{\mathrm{em}}\times \mathrm{BR}(\mu\to e\gamma) \\ \mathrm{CR}(\mu\to \text{ in N}) &\sim \alpha_{\mathrm{em}}\times \mathrm{BR}(\mu\to e\gamma) \end{aligned}}$$

- Sensitivities < 10^{-15} would go beyond MEG
- Crucial model discriminators





LC Chowdhury Masiero Patel Vempati '12

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Strong correlations:

not only seesaw models!

$$\boxed{\begin{aligned} \mathrm{BR}(\mu \to eee) &\sim \alpha_{\rm em} \times \mathrm{BR}(\mu \to e\gamma) \\ \mathrm{CR}(\mu \to \text{ in N}) &\sim \alpha_{\rm em} \times \mathrm{BR}(\mu \to e\gamma) \end{aligned}}$$

- Sensitivities < 10^{-15} would go beyond MEG
- Crucial model discriminators

In fact, there are models where $\mu \to eee$ and/or $\mu \to e$ conv. arise at tree-level.

Examples:

- SUSY with R-parity violation — e.g. Dreiner Kramer O'Leary '06
- Low-energy seesaw models — Abada et al '07
- Low-energy flavor models — LC Lalak Pokorski Ziegler '12

Rates enhanced wrt. $\mu \to e\gamma$!

TeV scale seesaw fields with large Yukawa couplings are possible (cancellations, flavor symmetry, inverse seesaw...)

example with n N_1 and n N_2: $L_{N_1} = +1\,,\ L_{N_2} = -1$

$$\begin{array}{cc} & \begin{array}{ccc} \nu_L & N_1 & N_2 \end{array} \\ \begin{array}{c} \nu_L \\ N_1 \\ N_2 \end{array} & \begin{pmatrix} 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\ Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix} \end{array}$$

"inverse seesaw" as in
Mohapatra, Valle '86
Gonzalez-Garcia, Valle '89
Branco, Grimus, Lavoura '89
Kersten, Smirnov '07
Abada, Biggio, Bonnet, Gavela, T.H. '07

soft L breaking: $\mu << M_N$

if Y_N is large, M_N not too high:

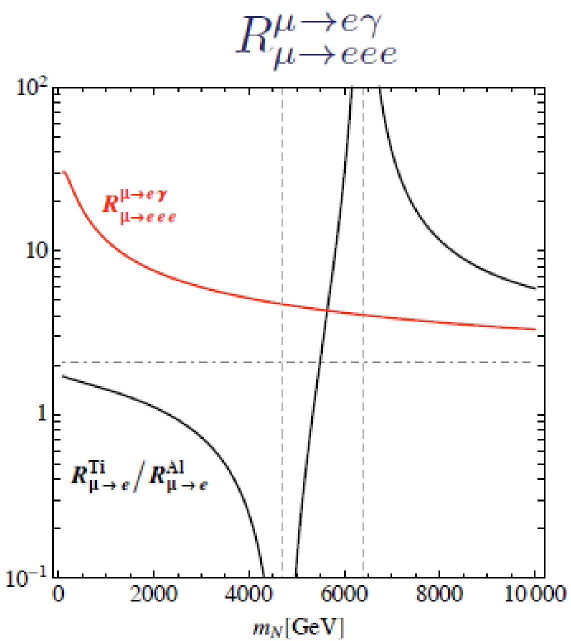
large CLFV with small neutrino masses: $m_\nu = Y_N^T \frac{\mu}{M_N^2} Y_N v^2$

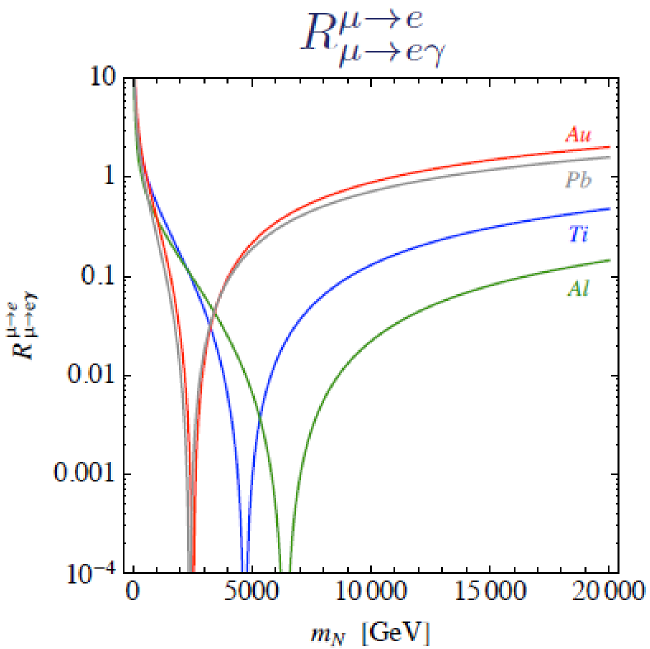
L is approximately conserved

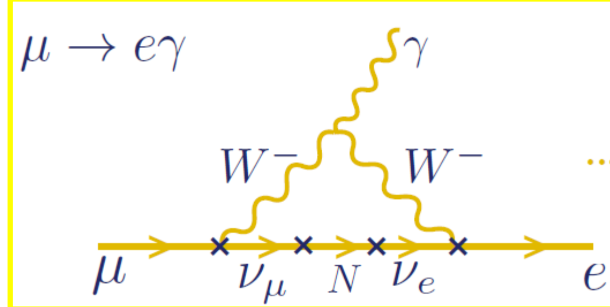
from T. Hambye's talk at the 1st Conference on CLFV, Lecce 2013

Potentially large LFV coupling to gauge bosons are induced, e.g.:

Type I μ-e transitions all generated at 1-loop







Alonso Dhen Gavela Hambye '13; Chu Dhen Hambye '12

μ→e conversion rate vanishes for different nuclei at different value of m_N!

Future prospects:

$$m_N \lesssim 6000\ \text{TeV} \cdot \left(\frac{10^{-18}}{R^{Ti}_{\mu\to e}}\right)^{\frac{1}{4}},$$

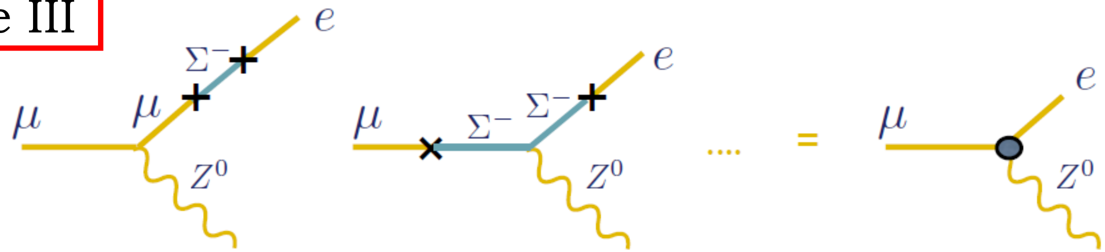
$$m_N \lesssim 1000\ \text{TeV} \cdot \left(\frac{10^{-16}}{R^{Al}_{\mu\to e}}\right)^{\frac{1}{4}},$$

$$m_N \lesssim 300\ \text{TeV} \cdot \left(\frac{10^{-14}}{Br(\mu\to e\gamma)}\right)^{\frac{1}{4}},$$

$$m_N \lesssim 1000\ \text{TeV} \cdot \left(\frac{10^{-16}}{Br(\mu\to eee)}\right)^{\frac{1}{4}}.$$

crucial property for CLFV in type-III seesaw: flavour mixing directly at the level of charged states

Type III

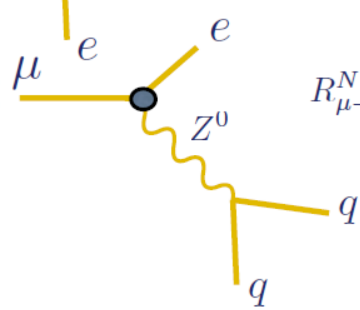


$\Rightarrow$ $\mu \to eee$: tree level

$$\Gamma(\mu \to eee) = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^\dagger_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot d^2$$

Abada, Biggio, Bonnet, Gavela, TH 07', 08'

$\mu \to e$ conversion : tree level



$$R^N_{\mu\to e} = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^\dagger_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot (b^N)^2$$

$\mu \to e\gamma$: still at one loop

$\Rightarrow$ ratios of 2 processes with same flavour transition: totally fixed!

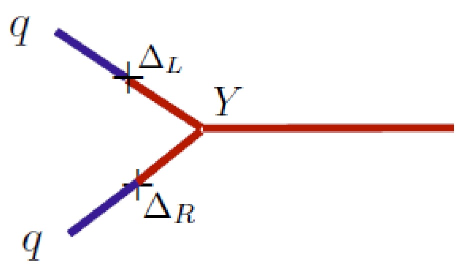
$$Br(\mu \to e\gamma) = 1.3 \cdot 10^{-3} \cdot Br(\mu \to eee) = 3.1 \cdot 10^{-4} \cdot R^{\mu\to e}_{Ti}$$

from T. Hambye's talk at the 1st Conference on CLFV, Lecce 2013

Composite Higgs

Another approach to naturalness:
Higgs field as a (pseudo) Nambu-Goldstone arising from new strong dynamics

- Linear couplings (partial compositeness)



$$y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R$$

$$\epsilon = \frac{\Delta}{m_Q}$$

$$\Delta_R \bar{q}_R \mathcal{O}_L \; + \; \Delta_L \bar{q}_L \mathcal{O}_R \; + \; Y \bar{\mathcal{O}}_L H \mathcal{O}_R$$

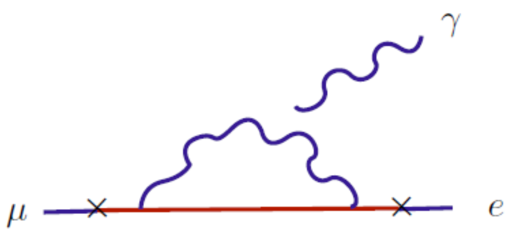
Two scenarios:

- Anarchic
- Minimal Flavor Violation

from M. Redi's talk at the 1st Conference on CLFV, Lecce 2013

Dipoles:

M. Redi '13



$$\left(\frac{y_*}{4\pi}\right)^2 \frac{e}{m_\psi^2} \left(\frac{\epsilon_L^\mu}{\epsilon_L^e} m_e \bar{\mu}_L \sigma^{\mu\nu} e_R + \frac{\epsilon_L^e}{\epsilon_L^\mu} m_\mu \bar{e}_L \sigma^{\mu\nu} \mu_R\right) F_{\mu\nu}$$

Most favorable choice:

$$\frac{\epsilon_L^i}{\epsilon_L^j} \sim \frac{\epsilon_R^i}{\epsilon_R^j} \sim \sqrt{\frac{m_i}{m_j}} \longrightarrow e\left(\frac{y_*}{4\pi}\right)^2 \frac{\sqrt{m_e m_\mu}}{m_\psi^2} \bar{\mu}\sigma^{\mu\nu} e F_{\mu\nu}$$

Estimate:

$$\mathrm{Br}(\mu \to e\gamma) \sim 5 \times \left(\frac{y^*}{3}\right)^4 \times \left(\frac{3\,\mathrm{TeV}}{m_\psi}\right)^4 \times 10^{-8} \longleftarrow \boxed{y^* \lesssim 0.2 \ \text{ or } \ m_\psi \gtrsim 50 \ \text{TeV}}$$

from M. Redi's talk at the 1st Conference on CLFV, Lecce 2013

Four final messages

New Physics @ TeV ? (hierachy problem? g-2?)
→ Natural to expect LFV effects
(e.g. SUSY, Partial Compositeness)

Many models already constrained
way beyond the LHC reach
(e.g. SUSY SO(10) with large mixing, anarchical PC)

$\mu \to e\gamma$, $\tau \to \mu\gamma$, $\mu \to eee$ and $\mu \to e$ conv. (*in different nuclei*)
complementary → crucial for model discrimination
(e.g. low-energy seesaw)

No solution to the hierachy problem?
LFV can test very high scales and give us hints about
the next fundamental scale